Digital Twin-Driven Process and Equipment Failure Mode, Effects and Criticality Analysis for Smart Manufacturing Applications

Sudipto Ghoshal[1], Jay Meyer[2], Venkat Malepati[3], Caleb Hudson[4], Somnath Deb[5], Andrew Hess[6], Feraidoon Zahiri[7] and Gregory Sutton[8]

[1,2,3,4,5]*Qualtech Systems, Inc., Rocky Hill, CT 06067, USA*

sudipto@teamqsi.com
jay@teamqsi.com
venkat@teamqsi.com
caleb@teamqsi.com
deb@teamqsi.com

[6]*Hess PHM Group, Easton, VA, USA*

andrew.hess@comcast.net

[7,8]*402d Commodities Maintenance Group, Warner-Robins Air Logistics Complex, Robins AFB, GA, USA*

feraidoon.zahiri@us.af.mil
gregory.sutton@us.af.mil

ABSTRACT

Qualtech Systems, Inc. (QSI)'s integrated tool set, consisting of TEAMS-Designer® and TEAMS-RDS® provides a comprehensive digital twin-driven and model-based systems engineering approach that can be deployed for fault management throughout the equipment life-cycle – from its design for fault management to condition-based maintenance of the deployed equipment. In this paper, we present QSI's approach towards adapting and enhancing their existing model-based systems engineering (MBSE) approach towards a comprehensive digital twin that incorporates constructs necessary for development of a Process Failure Mode, Effects and Criticality Analysis (P-FMECA) and integrates that with an equipment Failure Modes, Effects and Criticality Analysis (FMECA). The paper will discuss the various levels of automation towards incorporation of these model constructs and their reuse towards automation of the development of the different digital twins, and subsequently the automatic generation of the combined Process and Equipment FMECA. This automated ability to develop the integrated FMECA that incorporates both Process-level Failure Modes and Equipment-level Failure Modes allows the system designer and operators to correlate and identify process failures down to their root causes at the equipment-level, thereby producing a comprehensive actionable systems-level view of the entire Smart Manufacturing facility from a fault management design and operations perspective. The paper presents the application of this novel technology for the Advanced Metal Finishing Facility (AMFF) at the Warner-Robins Air Logistics Complex (WR-ALC) in Robins Air Force Base, Georgia, as part of WR-ALC's initiative towards model-based enterprise (MBE) and smart manufacturing.

1. INTRODUCTION

A modern automated complex manufacturing process comprises different sets of equipment working in concert on the products being manufactured as they make their way through the processing line to their desired form, fit and function. Each of these manufacturing processing lines with intricate dependencies between the process and the equipment results in a challenging environment for timely failure detection, accurate failure identification and corresponding mitigation.

As an example, consider a modern automated metal finishing facility for aircraft parts manufacturing or overhaul. The controllers for such manufacturing processes execute a large set of well-orchestrated sequences of processes such as cleaning, etching, rinsing, metal stripping, deoxidizing or pH neutralizing, coating, plating and others. Each of these processes executed correctly in sequence leads to the finished metal product that can pass various acceptance tests including visual inspections, corrosion resistance checks, adhesion tests

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etc. Any failure of these tests can lead to the rejection of not just that specific part but can also lead to the condemnation of the entire batch making such failures extremely expensive (communicated by AMFF engineers). The above failures can occur due to a whole host of factors that may include environmental factors such as incorrect temperature control, humidity control and process-related factors such as inadequate processing times, incorrect solution composition and contamination, as well as equipment-level failures which may have direct causal relationship with the aforementioned factors (communicated by AMFF engineers).

A thorough understanding of these process-level failures and their potential association with equipment-level failures and their effects on the finished product is essential to set up appropriate monitoring and preventive management of those failure effects. For effective failure management, which includes timely intervention to prevent critical failures as well as timely mitigation of unanticipated failures, the understanding and documenting of process-level and equipment-level failure modes and their effects is an essential first step in ensuring that an adequate failure management system can be put in place. An effective failure management system ensures continuous manufacturing operations and most importantly, that the finished product satisfies all requirements and passes all acceptance tests for it to be deployed. Failures that are not understood and not documented will likely not be adequately detected, and their root-cause(s) identified, isolated and corrected in a timely manner. This can lead to significant loss of material, time and resources for the facility and can even halt the production process. Thus, the first and foremost need that is essential for efficient and reliable operations at any modern manufacturing facility is a comprehensive understanding of the different potential failures in all of the processing stages that can lead to the product failing to meet its form fit and function related specifications. Hence, the development of an accurate FMECA that relates equipment failures that manifest as effects in terms of defects in the product being manufactured, is a first step.

A prior publication by Ghoshal et. al, 2019, titled “An integrated model-based approach for FMECA development for Smart Manufacturing Applications” and presented at the PHM Society’s 2019 conference described QSI’s cause-effect multi-function model-based systematic approach towards automated development of documents such as the FMECA, Dependency Analysis and Fault Trees for the identification of equipment-level failures, their propagation through the manufacturing system and the manifestation of those failures as undesirable effects during equipment operation. The current paper – a follow-up of the aforementioned publication, focuses on semi-automated digital-twin development of a complex manufacturing process along with models of the underlying equipment where the digital twin is key to the automatic generation of process-level FMECA development and its integration with equipment-level FMECA for the development of an overall system-level FMECA that relates the two and hence can be readily applied towards large and complex manufacturing processes.

The paper will conclude with the methodology adapted for the digital twin creation and the automatic generation and update of Process and Equipment FMECA for the process and equipment at the Advanced Metal Finishing Facility (AMFF) at Warner-Robins Air Logistics Complex (WR-ALC) (Figure 1). The results of the Process and Equipment FMECA lead to the adaptation of the digital twins for each of the chemical processing recipes with the corresponding equipment for each of the processing lines and provide the ability for continuous health assessment of the processes, drill down to their corresponding equipment health and

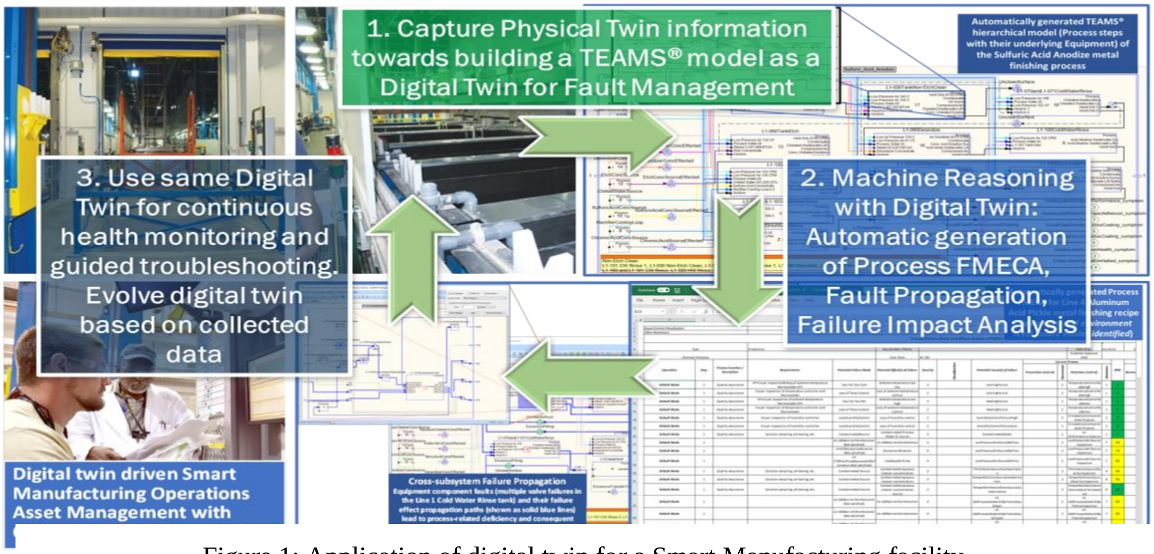


Figure 1: Application of digital twin for a Smart Manufacturing facility

facilitate guided troubleshooting, as necessary, for failure root-cause isolation and mitigation/recovery. It is anticipated that the same modeling methodology and software integration and deployment strategy, if proven to be successful at this facility, can be readily adapted for other similar smart manufacturing centers.

2. DIGITAL TWIN FOR FAULT MANAGEMENT

An accepted definition of a digital twin comes from Baricelli et.al., 2019, who described it as an intelligent virtual replica of a real-life cyber-physical system (CPS) useful in all phases of a system's lifecycle. While advances in computational sciences and simulation have led to various instantiations of digital twins that serve different purposes, a digital twin for fault management of a complex system has its set of unique challenges and likely requires a solution that can be easily developed and remains tractable and readily updateable through the lifecycle of the equipment.

Minimizing the lifecycle cost of a complex system requires a well-coordinated effort involving people of different expertise. In effect, the model is one of the key means by which people document and convey their understanding of the system, as it relates to their fields of expertise. For example, to the design engineer, the model could be a block diagram with transfer functions, whereas to a maintenance engineer, it is the schematic of replaceable components that make up the system. The objective is to develop a modeling methodology that is simple and intuitive enough so that people of various disciplines can understand and relate to it, yet powerful enough to be used during the entire lifecycle of a system. A key difference between a model that describes how an equipment operates versus how an equipment fails stems from the operational boundaries or constraints on the system function. To operate as desired, the equipment or system must perform within a constrained operational space that is sometimes referred to as success space. A Goal Function Tree (Johnson, 2013) is sometimes used to define that space. Failures, however, lead to the system "reside" outside that tight operational space. Often termed the failure space, it is significantly larger and more divergent than the success space and necessarily leads to the question as to what is of importance to the various stakeholders that must be modeled to define system behavior in the failure space. Trying to model all the ways an equipment can fail can quickly become prohibitively expensive even for relatively simpler systems.

QSI's TEAMS modeling methodology (Deb et. al, 1994, Ghoshal et al., 1999, Deb and Ghoshal, 2001) solves this aforementioned complexity by modeling the system from a failure space perspective through the incorporation of dependency relationships between functional failure effects and their causes through a causal graph structure. The causal graph model of the system captures functional failure effects and the component hierarchy and connectivity in the system, and relates the failure related effects, i.e., observations to their potential causes in terms of component faults in the connected hierarchical system (Figure 2).

The key to capturing the correct representation of the causal graph is an understanding of the functional decomposition of the system and using that knowledge to ascribe the functional failures to their corresponding component faults and their manifestations at their observation points, namely, symptoms, alarms, error codes, effects and diagnostic and prognostic tests. Fault propagation algorithms using the physical and functional connectivity between the components as captured from design documents or engineering judgment, allows the digital twin to determine which functional effects of faults propagate to which observation points. This explicit relationship between faults and effects is utilized by machine reasoning capabilities of TEAMS to rapidly determine the best explanation of observed failure behavior in terms of the

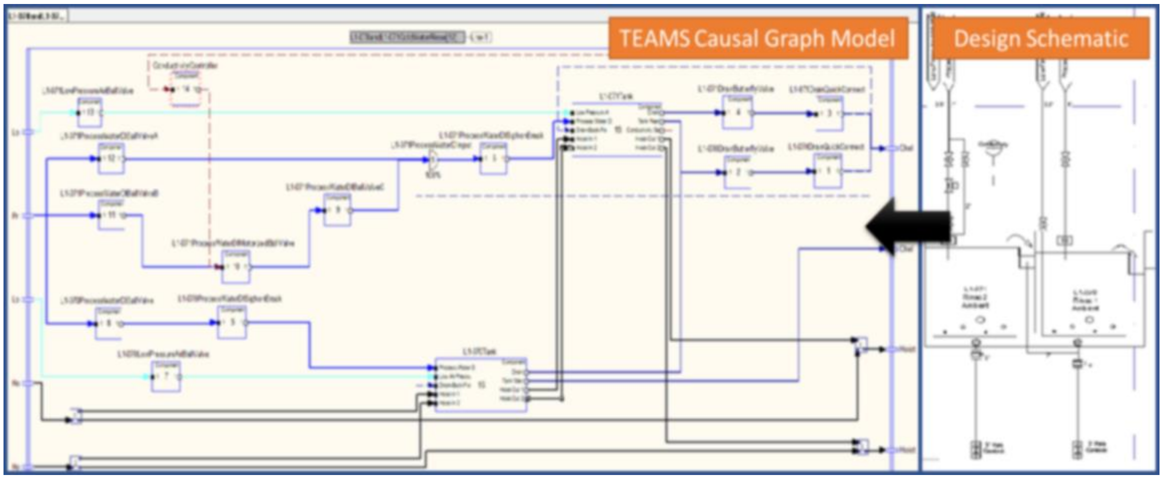


Figure 2: TEAMS Causal Graph Model representation of a system with a partial view of the design schematic of the system on the right. (Both views are blurred intentionally to protect confidentiality of the system design information).

underlying component fault(s) or degradation(s) thereby leading to an accurate and effective fault management design and decision-making. The causal relationship between faults, functions and effects as established in the TEAMS digital twin allows the tool to generate among others, detailed FMECA documents where with some necessary enhancements, it can relate process-level steps to the broader functionalities necessary for their success and identify corresponding failure modes, drilled down to the equipment level, that can cause that process step to fail. In addition, using attributes captured by the digital twin, we can readily compute the Risk Priority Number (Riggs, 2018) that is a key ingredient of any Process Failure Mode and Effects Analysis (PFMEA).

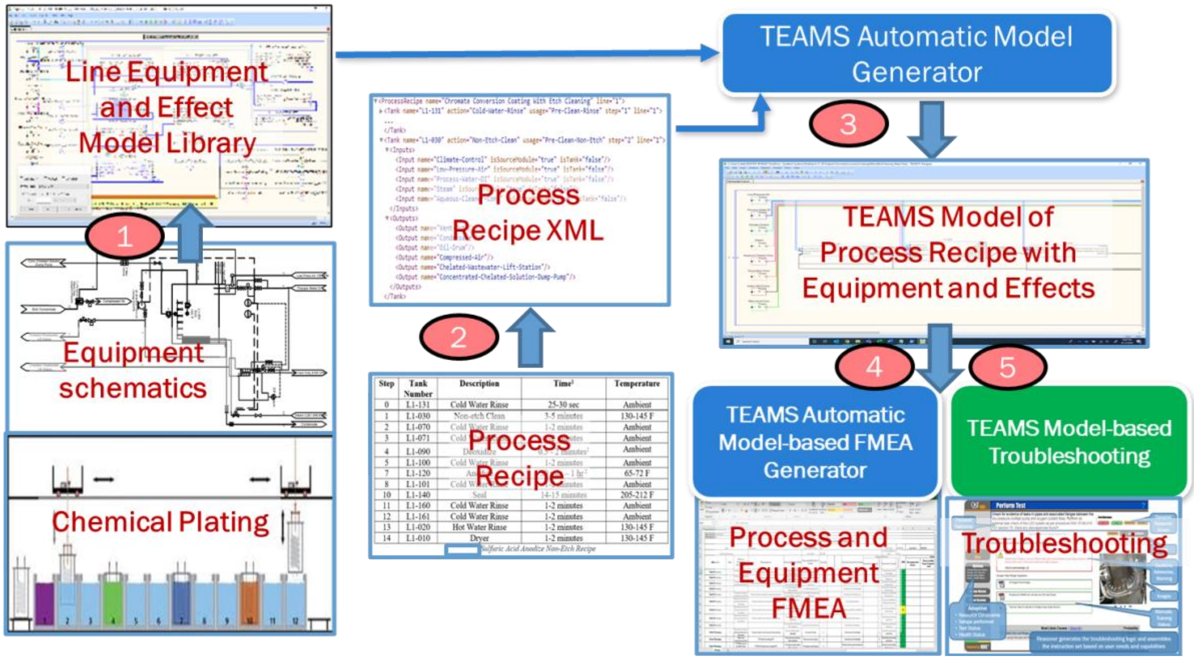
The next section of the paper details the methodology adopted to capture and automate the process for creating the digital twins of each of the metal finishing processes at the Advanced Metal Finishing Facility (AMFF) at Warner Robins Air Logistics Center (WR-ALC). The section also addresses the additional information capture and/or mapping to existing TEAMS digital twin constructs required to generate the combined Process and Equipment FMECA.

2.1. Application of the Digital Twin

Warner Robins Air Logistics Complex (WR-ALC), located at the Robins Air Force Base, Georgia, serves as the primary modernization, sustainment, and depot maintenance center for a variety of aircraft, including the U-2, C-5, C-17, all models of the C-130, E-8, and F-15, and other strategic special aircraft. One of the critical, new, state-of-the-art manufacturing facilities at WR-ALC is the Advanced Metal Finishing Facility (AMFF). The AMFF is one of the largest metal finishing facilities in the world with nine separate automated metal plating and finishing lines with over 160 large chemical processing tanks in the wet area through which metal aircraft parts are cleaned, plated and finished. AMFF is used to finish both new and renewed metal aircraft parts. It is a critical facility for aircraft parts depot maintenance at Warner Robins.

While full automation of the complex metal finishing process lead to significant benefit in workplace safety and environment, the large number of metal finishing recipes that are supported, associated equipment, their controls, their timing and orchestration that comprise the entire metal finishing process, often make it a significant challenge for determination of root causes and remedy when any of the acceptance tests for the finished aircraft part fails.

Qualtech Systems, Inc. (QSI) and WR-ALC are addressing the above challenge with the proposed adaptation and deployment of TEAMS® technology for ***designing and implementing a consistent, systematic and repeatable model-based process and methodology for Fault Management Analysis, Design and Deployment for metal***



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   ...
  </Tank>
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     <Output name="Compressed-Air"/>
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     <Output name="Concentrated-Chelated-Solution-Dump-Pump"/>
   </Outputs>
  </Tank>
```

Step	Tank Number	Description	Time¹	Temperature
0	L1-131	Cold Water Rinse	25-30 sec	Ambient
1	L1-030	Non-etch Clean	3-5 minutes	130-145 F
2	L1-070	Cold Water Rinse	1-2 minutes	Ambient
3	L1-071	Cold [illegible]	[illegible]	Ambient
4	L1-090	Deoxidize	[illegible]	Ambient
5	L1-100	Cold Water Rinse	1-2 minutes	Ambient
7	L1-120	An[illegible]	[illegible] – 1 hr¹	65-72 F
8	L1-101	Cold W[illegible]	[illegible]	Ambient
10	L1-140	Seal	14-15 minutes	205-212 F
11	L1-160	Cold Water Rinse	1-2 minutes	Ambient
12	L1-161	Cold Water Rinse	1-2 minutes	Ambient
13	L1-020	Hot Water Rinse	1-2 minutes	130-145 F
14	L1-010	Dryer	1-2 minutes	130-145 F

Sulfuric Acid Anodize Non-Etch Recipe

Figure 3: QSI's solution approach towards automated development of digital twin of a smart manufacturing facility and generation of tailored Process and Equipment FMECA and Guided Troubleshooting

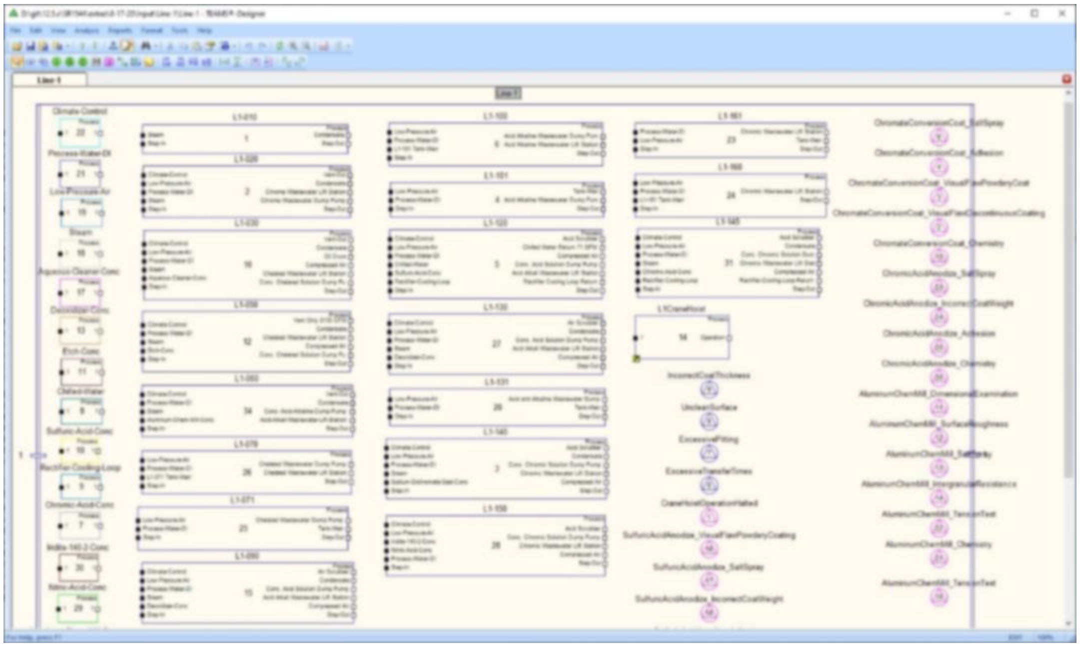


Figure 4: Library of equipment used in Line 1 at the AMFF for all the different process recipes the line supports. (Figure has been intentionally blurred to ensure confidentiality of the system design information)

finishing at the AMFF. The QSI technology with the use of the proposed adaptations can also be readily deployed with rapid benefits realization at other process-oriented manufacturing facilities that are part of WR-ALC's overall Smart Manufacturing Ecosystem initiative (see video link: https://youtu.be/D_eTd3QR384).

As a key step towards achieving the above goal, QSI and WR-ALC team is adapting QSI's commercial TEAMS Designer product suite (Figure 3) towards rapid ingestion of process and design-related information towards automated digital twin development of the process and the equipment (*Steps 1, 2 and 3 in Figure 3*) and the subsequent usage of the digital twin for automated generation of Process-level Failure Modes and Criticality Analysis also called Process-FMECA (*Step 4 in Figure 3*). Process-FMECAs are an essential step in the development and implementation of a Fault Management of complex processes such as industrial manufacturing and finishing of aircraft parts. The Process-FMECA, integrated with Equipment-level FMECA, through the usage of QSI's TEAMS software will allow the Air Force end-users such as the Chemical Engineers and Maintenance Technicians at the AMFF to perform sensor gap analysis for improved diagnostics as well as automatically generate and display step-by-step troubleshooting procedures on the technician's PC, monitoring station or mobile devices (*Step 5 in Figure 3*). This ability can help in providing significant benefits through rapid and consistent turn-around times for finishing of aircraft parts and thereby increase aircraft availability and their mission readiness.

3. INFORMATION CAPTURE AND AUTOMATION TOWARDS DIGITAL TWIN DEVELOPMENT

The foundation of TEAMS® automated digital twin creation that represents the various processes and equipment configuration underlying the different metal finishing recipes methodology is based on the following concepts:

First, we developed a library of individual models of each of the tanks for each of the lines which could then be strung together virtually much like the physical twin based on the individual requirements of the metal finishing process, thereby forming the entire digital twin for each process being implemented with the corresponding equipment at the facility.

Many complex manufacturing processes are implemented as a string of equipment operating in an orchestrated manner as part of a manufacturing/assembly line that are implementing various steps of the manufacturing process. The AMFF at WR-ALC is no exception. Each of the different manufacturing lines at the AMFF essentially comprise of an electromechanical hoist that can travel along the line and a series of tanks along the line that fulfil specific steps in the finishing process. For example, a Chromate Conversion Coating process comprise of the following essential process steps, namely Non-Etch Cleaning, Etch Cleaning, Rinsing, Deoxidation and Chemical Conversion. Each of these process steps are conducted at different tanks along the line with the appropriate chemical composition in the tanks with specific environmental controls, such as temperature, mechanical stirring and the length of time the process step takes. Another metal finishing process on the same line may use the same set of tanks but with different environment controls and in a different sequence. An example of such a TEAMS library comprising of all tanks and equipment are shown in Figure 4.

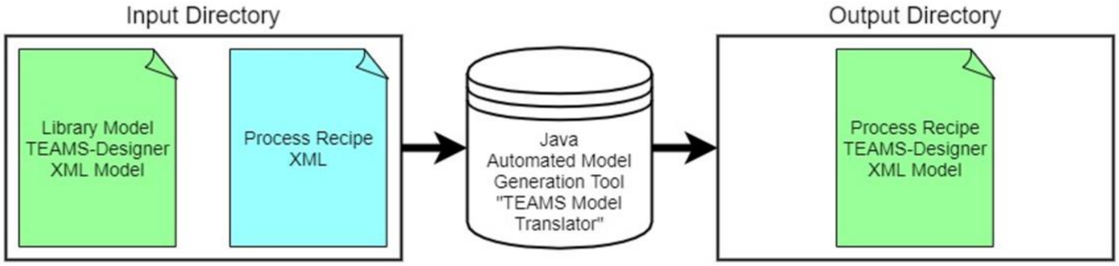
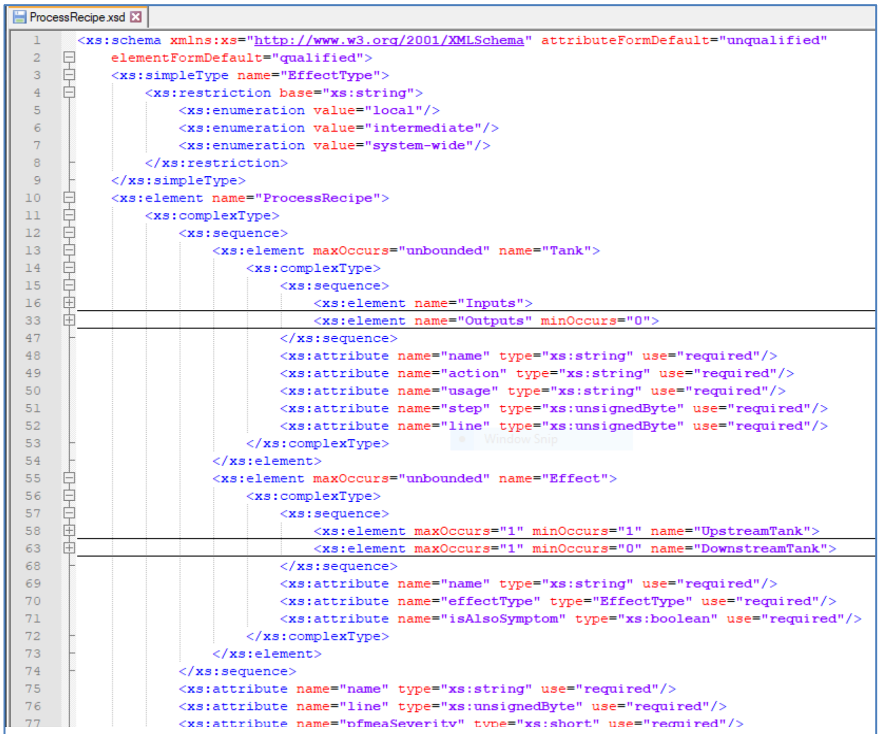


Figure 5: Automated TEAMS digital twin development process for any Process Recipe

Second, we developed an XML-based method to capture the process recipe and a Model Assembler which used the XML Process recipe as a guide and automatically assembled the entire digital twin of the Line for that Process Recipe using elements from the TEAMS model element library for the entire facility (Figure 5). The entire capability was developed with a focus on ensuring that this methodology is sufficiently general enough and can be rapidly adapted for auto-generation of TEAMS digital twins for other manufacturing facilities.

While Process Recipes and tank configurations/equipment may not often change, there are times when tanks that perform the same general functions are interchanged. For example, if the process recipe for Chromate Conversion Coating calls for a Post-Etch Rinse in Tank L1-070 (a cold-water rinse tank), but that tank is down due to maintenance, the recipe and operators can use a different cold water rinse tank such as L1-160. While this may not affect the performance of the Chromate Conversion Coating Process, this does affect the performance of a diagnostic model. In order to correct this, typically another model would need to be constructed, this time using L1-160 in place of L1-070. Such reconfigurations in addition to the creation and potential of modification of existing Process Recipes, necessitated a flexible automated and rapidly deployable model generation capability.

TEAMS Models can be imported to and exported from TEAMS-Designer, QSI's digital twin development and analysis environment, in an XML format. For the purposes of



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    elementFormDefault="qualified">
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            <xs:enumeration value="local"/>
            <xs:enumeration value="intermediate"/>
            <xs:enumeration value="system-wide"/>
        </xs:restriction>
    </xs:simpleType>
    <xs:element name="ProcessRecipe">
        <xs:complexType>
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Figure 6: Process Recipe XML Schema Definition (XSD)

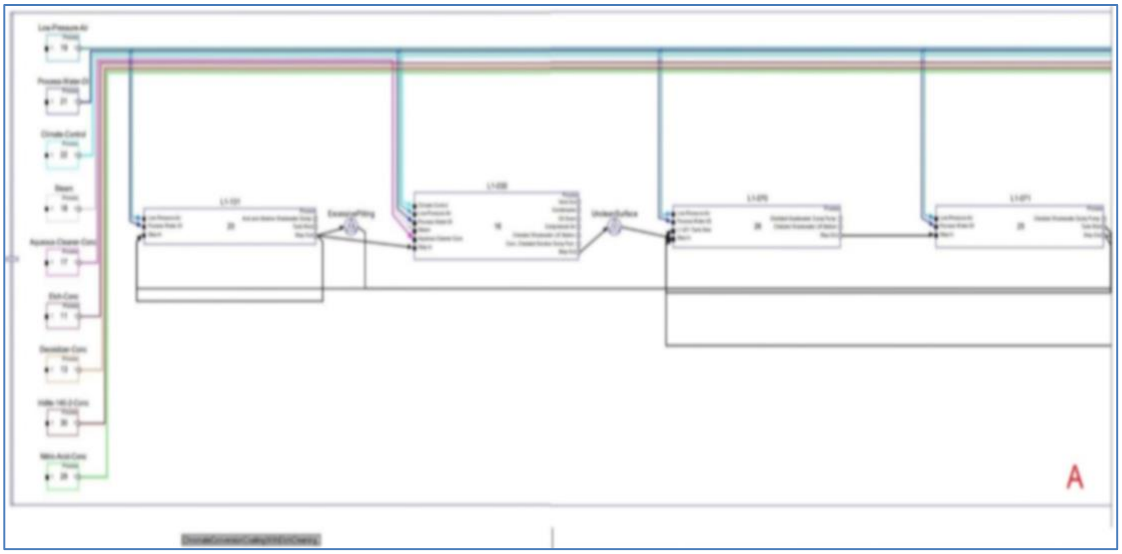
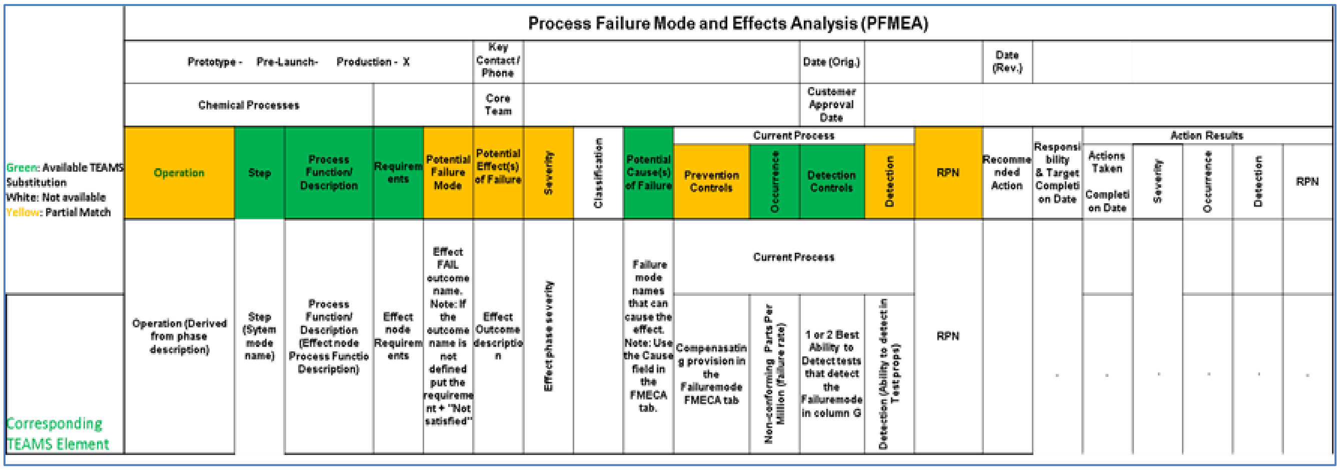


Figure 7: A small section of the “Chromate Conversion Coating with Etch Cleaning” digital twin autogenerated by TEAMS. (Figure has been intentionally blurred to ensure confidentiality of the system design information)

this solution deployment, QSI has developed a new XML Schema Definition (XSD) that defines process recipes in an XML format (Figure 6). The document specifies which tanks in the library model are used, their order, their inputs and outputs, and their various inter-tank interactions involved for a process recipe. The document also specifies the various intermediate and end-effects to be placed in the model for improved Process FMEA modeling.

Once a user has developed a process recipe XML (that has been validated for format and content with the XSD), it can be used with the TEAMS Library Model XML (for the line the recipe is conducted on) to produce a TEAMS model of the process using the TEAMS Model Translator Application (Figure 7). This process ensures ease in making updates across all process recipe models, as the user will only need to update the library model and re-run the TEAMS Model Translator for the affected recipe models.

The output of the model creation process as implemented in the “TEAMS Model Translator” is an XML version of the TEAMS model of the entire Process Recipe as implemented in that AMFF line with all the equipment, failure modes, diagnostic tests, alarms, interim and end-effects. The fully functional XML model can be loaded in TEAMS Designer which has been enhanced and adapted for the automatic creation of Process and Equipment FMECA and combining them, if desired, for the generation of a system-level comprehensive FMECA tailor-made for each Process Recipe and their corresponding line and their equipment.



	Process Failure Mode and Effects Analysis (PFMEA)																				
	Prototype - Pre-Launch- Production - X					Key Contact / Phone						Date (Orig.)			Date (Rev.)						
	Chemical Processes					Core Team						Customer Approval Date									
										Current Process							Action Results				
Green: Available TEAMS Substitution White: Not available Yellow: Partial Match	Operation	Step	Process Function/ Description	Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Classification	Potential Cause(s) of Failure	Prevention Controls	Occurrence	Detection Controls	Detection	RPN	Recommended Action	Responsibility & Target Completion Date	Actions Taken Completion Date	Severity	Occurrence	Detection	RPN
	Operation (Derived from phase description)	Step (Sytem mode name)	Process Function/ Description (Effect node Process Functio Description)	Effect node Requirements	Effect FAIL outcome name. Note: If the outcome name is not defined put the requirement + "Not satisfied"	Effect Outcome description	Effect phase severity		Failure mode names that can cause the effect. Note: Use the Cause field in the FMECA tab.	Current Process				RPN							
Corresponding TEAMS Element										Compensasting provision in the Failuremode FMECA tab	Non-conforming Parts Per Million (Failure rate)	1 or 2 Best Ability to Detect tests that detect the Failuremode in column G	Detection (Ability to detect in Test props)								

Figure 8: Process FMEA (PFMEA) elements as described in AS13004 and corresponding TEAMS elements that are adapted to align with the AS13004 PFMEA constructs

4. AUTOMATIC PROCESS AND EQUIPMENT FMECA GENERATION FROM THE TEAMS DIGITAL TWIN

In order to generate the PFMEA as per the Air Force preferred AS13004 format, we needed to capture additional process related data that are not part of a traditional graphical causal model used for fault diagnostics and prognostics design. Some of the AS13004 data elements are currently captured in the models developed in TEAMS-Designer, and for some elements, we have designed and enhanced various TEAMS data capture fields as well built-in methodologies to generate some of the AS13004 PFMEA constructs. A key objective towards making those enhancements was an attempt to ensure that the model developer community can readily capture such information with minimal relearning of any user interface and leverage most of the use cases for the existing TEAMS modeling constructs.

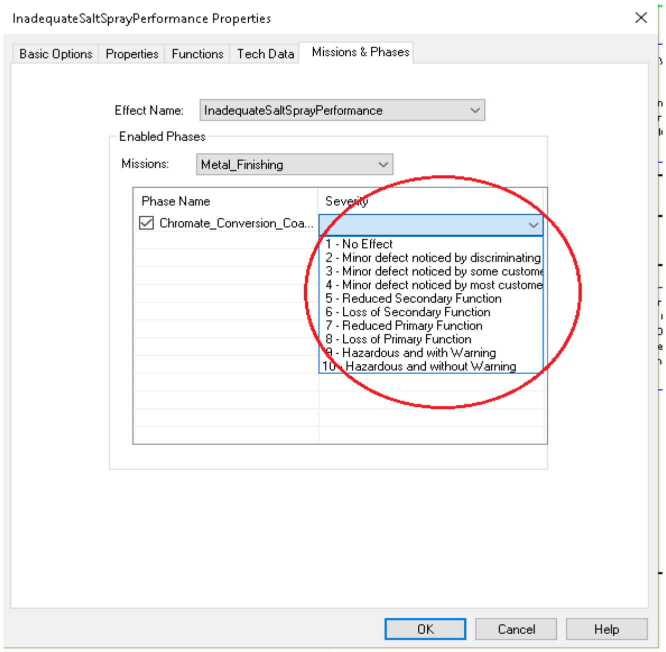
The AS13004 PFMEA data that we can currently capture in TEAMS-Designer, and the TEAMS data fields we adapted and enhanced to capture the rest of the AS13004 entities are shown in Figure 8. The data elements that could be readily mapped and modeled in TEAMS-Designer for PFMEA, using existing elements are shown in Green, and data elements that were captured through additional enhancements and retooling are shown in yellow in Figure 8.

Details of the AS13004 PFMEA report columns and the corresponding TEAMS element in parenthesis that we capture in TEAMS-Designer model are shown below. We chose the following interpretation of the AS13004 constructs after consulting subject matter experts from WR-ALC who are well versed in the AMFF metal finishing processes as well as experts in risk and reliability analysis.

- Operation (Phase/Sequence of system modes)
- Step (System mode Sequence # corresponding to mission/phase)
- Process Function/Description (Process description captured in Effect Node Properties),
- Requirements (Requirements captured in Effect Node Properties),
- Potential Failure Mode (Effect Outcome Name),
- Potential Effect(s) of Failure (Effect Outcome Description)
- Severity (Effect Severity which can differ based on the Phase)
- Classification (N/A)
- Potential Cause(s) of Failure (Failure Modes causing the effect modeled as failure modes in the model)
- Prevention Controls (Compensating Provisions captured in failure mode properties)
- Occurrence (Non-Conforming Parts (PPM) captured under Reliability tab of Failure modes properties windows)
- Detection Controls (Modeled test with lowest score/lowest difficulty)
- Detection (Captured as Test Difficulty of a Test that detects the Failure mode)

The following section describes TEAMS adaptations for some of the key data elements of AS13004 PFMEA.

Failure Severity in AS13004 standard ranges from 1-10. In TEAMS-Designer, we decided to capture these severity rankings under the effect Properties as effect severity for that operating or manufacturing operational phase as shown in Figure **9**. While generating Process and Equipment FMECA, we will use the highest severity among all the effects that result from the failure mode listed in the *Potential cause of the failure* column in the PFMEA.



InadequateSaltSprayPerformance Properties

Effect Name: InadequateSaltSprayPerformance

Enabled Phases

Missions: Metal_Finishing

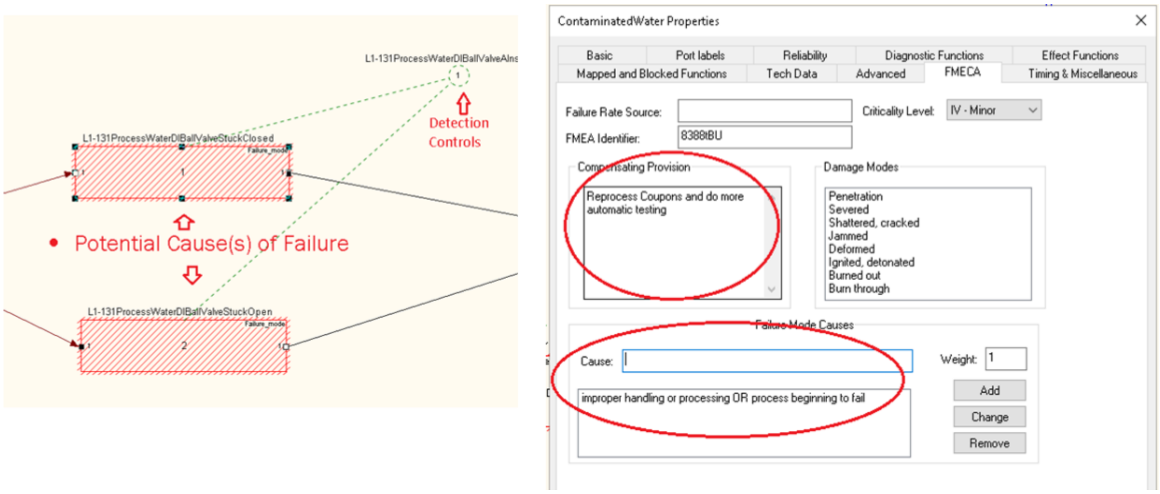
Phase Name	Severity
☑ Chromate_Conversion_Coa...	

1 - No Effect
2 - Minor defect noticed by discriminating
3 - Minor defect noticed by some custome
4 - Minor defect noticed by most custome
5 - Reduced Secondary Function
6 - Loss of Secondary Function
7 - Reduced Primary Function
8 - Loss of Primary Function
9 - Hazardous and with Warning
10 - Hazardous and without Warning

Figure 9: AS13004 Severity risk captured as an effect severity in TEAMS Designer

The Potential Causes of Failure element of the PFMEA are directly mapped to failure modes in the TEAMS model that can cause certain effects. The failure modes are the lowest level modules in the TEAMS-Designer model. For *Prevention Control* column, we utilize the Compensating Provision field available in Failure Mode properties dialog as shown in Figure 10.

Occurrence score in PFMEA captures the relative ranking of the likelihood of the Failure Mode being caused by the *Potential Cause of Failure* identified earlier. We capture this as a modified failure rate field that currently exists in the



ContaminatedWater Properties

Failure Rate Source:

Criticality Level: IV - Minor

FMEA Identifier: 8388tBU

Compensating Provision: Reprocess Coupons and do more automatic testing

Damage Modes:
Penetration
Severed
Shattered, cracked
Jammed
Deformed
Ignited, detonated
Burned out
Burn through

Failure Mode Causes

Cause:

Weight: 1

improper handling or processing OR process beginning to fail

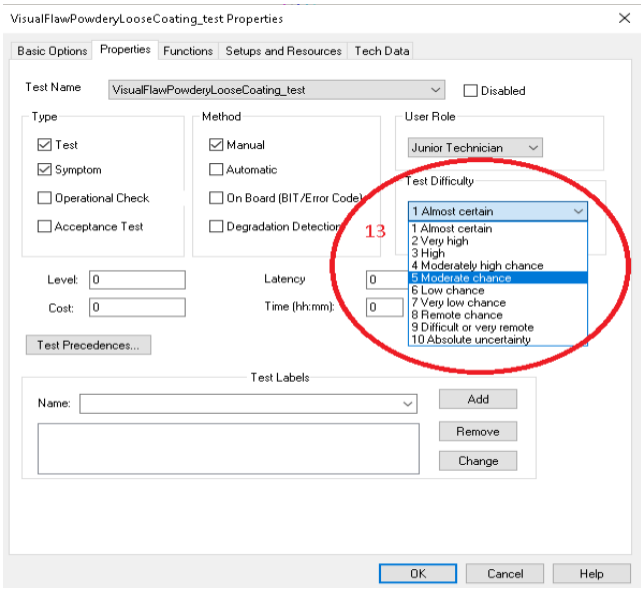
Figure 10: Potential cause(s) of failure and Prevention Control

Failure Mode properties as a simple drop-down that is consistent with the distribution intervals of the Process PPM element in AS13004.

Detection Controls are a key element in PFMEA because of its role in generating the Risk Priority Number (RPN). In TEAMS model *Detection Controls* are the tests modeled to detect the Failure Modes (*Potential Causes(s) of Failure* in PFMEA). *Detection* is the rank associated with the *Detection Control* based on the ease/difficulty of detecting the specific failure mode. For capturing *Detection* scoring in the TEAMS model, we have decided to introduce new element called Test Difficulty that captures the ease of performing the test as shown in Figure **11**. This allows us to use the test with the lowest detection (easiest to perform) ranking, in the Risk Priority Number (RPN) calculation.

RPN, as per AS13004 (Riggs, 2018 and the SAE AS13004 standard), is calculated by multiplying the highest severity failure mode number with the highest occurrence potential failure and multiplied with lowest detection score. Accordingly, in TEAMS-Designer, we compute RPN using the following fields as stated – Severity, i.e., the highest severity Effect caused by the failure mode, is multiplied with Occurrence, i.e., the failure mode Occurrence score, multiplied with Detection, which is the lowest Difficulty score among all test s that detect the failure mode, i.e., the lowest score (easiest to perform) test that can detect the failure mode.

See Figure 12 for an automatically generated combined Process and Equipment FMECA with color-coded RPN number. The color-coding scheme, which is customizable, was provided by the WR-ALC subject matter experts as part of their desired AS13004 compliant PFMEA template.



VisualFlawPowderyLooseCoating_test Properties

Test Name: VisualFlawPowderyLooseCoating_test

☐ Disabled

Type:
☑ Test
☑ Symptom
☐ Operational Check
☐ Acceptance Test

Method:
☑ Manual
☐ Automatic
☐ On Board (BIT/Error Code)
☐ Degradation Detection

User Role: Junior Technician

Test Difficulty: 1 Almost certain
1 Almost certain
2 Very high
3 High
4 Moderately high chance
5 Moderate chance
6 Low chance
7 Very low chance
8 Remote chance
9 Difficult or very remote
10 Absolute uncertainty

Level: 0

Cost: 0

Latency: 0

Time (hh:mm): 0

Name:

Figure 11: Test Detection Score captured as Test Difficulty in TEAM Model

As part of implementation method for creation of the AS13004 PFMEA and its combination with the existing Equipment FMECA, TEAMS-Designer performs the analysis using the digital twin represented by the causal graph model of the specific process and equipment. The analyses include rapid computation of dependency-matrices for different selected System Modes (key operational steps of the processes such as those that require changing and/or turning on or off of the individual equipment such as valves, pumps etc.) and the generation of the FMECA information derived from that process-step and operating mode-specific dependency relationship between the equipment failure causes and process failure related effects captured in the digital twin. We use an XML based schema driven open

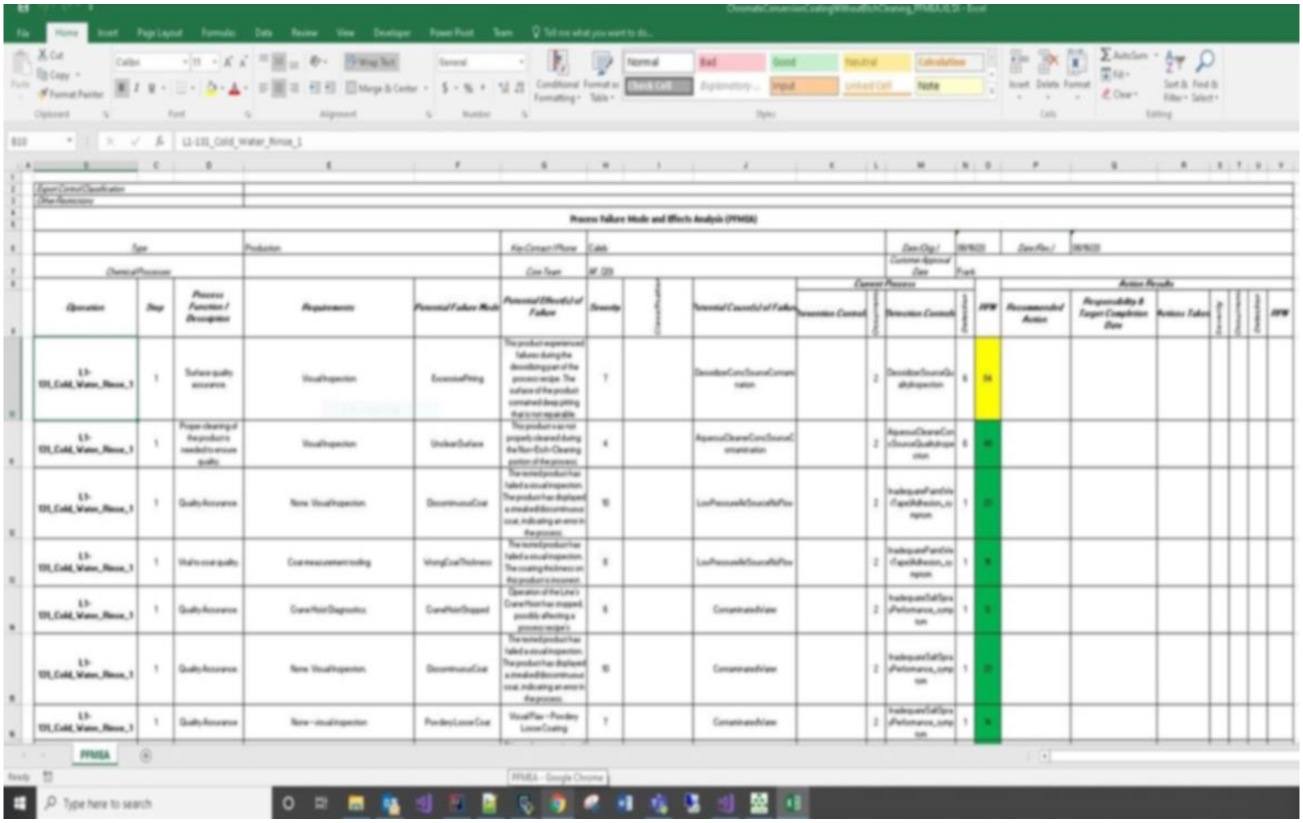


Figure 12: An Excel spreadsheet view of a combined Process and Equipment FMECA for a specific metal finishing recipe at AMFF *(Figure has been intentionally blurred to ensure confidentiality of the system design information).*

approach that allows ready transformation of the FMECA information using stylesheets towards the creation of the FMECAs in interactive HTML, Excel as well as PDF using the exact format as specified in the template provided by WR-ALC subject matter experts (Figure 12).

5. CONCLUSIONS

Significant life cycle cost savings can be achieved through improved fault management design of a smart manufacturing facility through effective usage of a digital twin-based system engineering approach. Rapid generation and updating of the digital twin is key to ensuring its relevance and continue providing the desirable benefits from its usage throughout the life cycle of the manufacturing facility through all its configuration changes and technology refreshes. The adoption of a digital twin such as TEAMS can address such aspects of Fault Management design and operations spanning Design for Testability, Process and Equipment FMECA generation, continuous asset health monitoring and guided troubleshooting.

Developing a useful and easy-to-develop and update digital twin for fault management can be challenging. The paper discusses one such approach that uses the common knowledge representation of the system through the capture of a causal graph model in the form of a functional failure effect dependency model that can be used at every stage of the system lifecycle and can provide the basis for real-time health assessment, condition monitoring and guided troubleshooting. Usage of such high-level causal models as fault management digital twin readily lends itself towards rapid automation and extension and enhancement of its analytical capabilities such as towards modeling processes and generating Process FMEAs as described in the paper. Using the automated methodology developed as described in the paper, QSI successfully generated comprehensive Process and Equipment FMECAs for all 50 metal finishing recipes that are currently in use for all of the lines in the AMFF for usage by the AMFF engineers. QSI is currently helping WR-ALC institutionalize this capability and knowledge with the digital twins as the cornerstone for the AMFF engineers whereby they can rapidly update the digital twins and generate additional FMECAs based on any configuration change, equipment changes and recipe modifications.

As part of our ongoing research, we anticipate extension of such fault management digital twins with causal reasoning in the areas of cross system fault propagation and impact assessment for highly modular applications such as the NASA’s Lunar Gateway in the near future.

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BIOGRAPHIES

Sudipto Ghoshal, **Ph.D.**, **VP of Engineering** at Qualtech Systems, Inc. (QSI), received his B. Tech degree in Electrical Engineering from the Indian Institute of Technology, Kharagpur, India in 1989, the M.S. and Ph.D. degrees in Biomedical Engineering from the University of Connecticut, Storrs in 1991 and 1997, respectively and an MBA from Indiana University, Kelley School of Business, Bloomington in 2009. His research at QSI primarily involves developing and implementing algorithms for highly scalable, compact diagnostic reasoning engines and architecting the test implementation modules for the TEAMS-RDS® software framework. He is a committee member of IEEE SCC20 Diagnostics and Maintenance subcommittee since 1991 and has played an active role in developing standards for system diagnosis. He, along with several colleagues at QSI, holds a patent for inventions related to a distributed architecture for system diagnosis. He has published numerous journal and conference papers and has received several best paper awards in technical conferences. He was a recipient of the 2002 & 2008 NASA Space Act Award for "A Comprehensive Toolset for Model-based Health Monitoring and Diagnosis."

Jay Meyer, Level 2 Software Engineer at Qualtech Systems, Inc., received in BS in Electrical Engineering from the University of Connecticut in 2016. He is an expert in software development for algorithms and user interface design and played key architecture and implementation role in the development of the latest versions of the TEAMS Designer software. He was the technical lead for the effort with Warner Robins Air Logistics Complex which is the subject matter of this paper.

Venkat Malepati, Director of Product Development and Support received his MS in Electrical Engineering from the University of Connecticut in 1999. His research involves development of algorithms and their implementation for real-time embedded equipment health monitoring and assessment. In addition to managing the Product development and associated research at QSI, he has key responsibility towards product support for QSI's commercial and Government customers. He was the lead developer of the Process and Equipment FMECA generation capabilities as incorporated in QSI's TEAMS suite of products.

Caleb Hudson, Research Engineer at Qualtech Systems, Inc. received his undergraduate degree from Florida State University and has multiple certifications in Machining and Manufacturing; CNC Programing; Advanced CNC Operation; IPC Solder and Electronics Specialist. Caleb has extensive experience in mechanical design and prototyping, electronics prototyping, machining, plastics CNC, and various other manufacturing processes. He has developed and commercialized highly specialized oceanographic instruments for use in scientific and petroleum research and tracking. He has collaborated with armed forces personnel on-site at Robins AFB to track the process for remanufacturing C-130 propeller blades while supporting the efforts of academic and engineering personnel to develop AI and machine learning processing for inspection data outputs. He is a Military veteran with over 3 years of experience in working within and successfully leading a small team in high stress environments both in the United States and abroad. Acquired extensive knowledge in communication, performance critiquing and asset management. Recipient of several awards for outstanding performance and professionalism. Career supported by Associates in Arts degree.

Somnath Deb, Ph.D., President, CTO at Qualtech Systems, Inc. (QSI), received the M.S. and Ph.D. degrees in Control and Communication Systems from the University of Connecticut (UCONN) in 1990 and 1994, respectively. In 2013, he was inducted into the UConn Academy of Distinguished Engineers for outstanding contributions to the School of Engineering and to the engineering profession. His research interests include Integrated Diagnostics and Vehicle Health Management Architectures and Solutions, embodied in QSI's TEAMS® tool suite for design for service, real-time embedded diagnostics, tele-diagnosis, and guided troubleshooting solutions. He has published over 50 journal and conference papers. He received the Best Technical Paper Awards at the 1990, 1994, 2001 AUTOTEST Conferences and the NASA Space Act Awards in 2002 and 2008 for his work on tools for model-based testability analysis, guided troubleshooting, and remote health monitoring.

Andrew Hess is a 1969 graduate of the University of Virginia (BS Aerospace Engineering) and the U. S. Navy Test Pilot School. He has completed many Navy and DOD sponsored professional and acquisition management courses. He is world renowned for his work in fixed and rotary wing health monitoring and is recognized as the father of Naval Aviation propulsion diagnostics. Working for the Naval Air System Command and beginning with the A-7E Engine Monitoring System program of the early 70's, he has been the leading advocate for health monitoring in the Naval Aviation. He has been actively involved in every NAVAIR aircraft program since the F-8, leading to the evolution and development of not just engine monitoring; but also aircraft structural life usage, avionics systems, mechanical systems, and comprehensive health monitoring and management capabilities for most all other aircraft subsystems and advance maintenance concepts like Condition Based Maintenance (CBM+). For the last 10 years of his government career, he worked leading and managing the vision, the development, and integration of the Prognostic and Health Management (PHM) system the AL support concept for the Joint Strike Fighter F-35 program. His current consulting services and interests are now leading him and his clients to exploring the application of PHM capabilities, predictive analytics, CBM+, and asset management related support concepts to many diverse industry sectors such as: aerospace, industrial gas and steam turbines, ships and fast patrol boats, unmanned vehicles, wind energy, nuclear energy, ground vehicles, mining, and gas and oil. Serving on the Board of Directors, he helped establish and grow the new and very successful PHM Society professional organization and is the current president of the society. He was named an Asset Management Fellow with the International Society of Engineering Asset Management, is a NAVAIR Senior Engineering Fellow, and is a member of the SAE E-32 committee on Propulsions System Health Monitoring, the SAE HM-1 committee on Integrated Vehicle Health Management Systems and is a prognostic lead for the ISO committee on condition monitoring. He has been long and very active as the organizing chair for the Advanced Diagnostic and PHM Track at the annual IEEE Aerospace Conference. He has published a large number significant peer group reviewed technical papers and has co-authored a widely used textbook on prognosis of engineering systems. In his current consulting role he has provided extensive support to a sundry of OEM's, government and research organizations, academia, and small businesses. Recently, he has been very engaged with the University of Cincinnati IMS Center in regard with growing and implementing PHM capabilities to Smart Manufacturing and Industry AI applications. Most recently, he has been professionally recognized as a PHM Fellow (2019) and with a lifetime achievement award for PHM.

Feraidoon Zahiri, Engineer at the US Air Force, received his Master of Science degree in Engineering Mechanics from Penn State University. He has more than 20 years of experience in technology research, development, and transition in numerous scientific and engineering disciplines. He has overseen large-scale decision-support projects incorporating analytics, simulation, and visualization for resource allocation, system troubleshooting and repair, and data-driven predictive maintenance. He was selected as a winner of the Small Business Technology Council's (SBTC) 2017 "Champion of Small Business Technology Commercialization" Award, for his role in filling a critical technology gap in the Air Force Sustainment community. He has played a critical role in providing opportunities for small business to promote the technology across all DoD services, boosting their technology transition even further. He has been instrumental in testing and transitioning new technologies developed through the CTMA (Commercial Technologies for Maintenance Activities) program for the past several years including a new advanced ATE (Automated Test Equipment) for testing electrical subsystems and more recently, the application of a new Voice-enabled Inspection System, VIMS (winner of the 2016 CTMA Partners Technology Challenge). He has been a strong government advocate of the CTMA program.

Gregory Sutton, Engineering Director at 402d Commodities Maintenance Group, Warner-Robins Air Logistics Complex, received his Bachelor of Mechanical Engineering at Georgia Institute of Technology in 1993 and Masters of Logistics Administration at Georgia College & State University in 2009. He began his civilian service in 2002 as support equipment engineer before leading Technology Insertion across Robins AFB then helping create the first, new Airworthiness certification for the CV-22 in 2010. He currently oversees the process, equipment, and facilities engineering for a large depot maintenance industrial operation with an annual labor and material budget of $147M across 32 facilities. The Engineering Squadron consists of 65 engineers, technicians, He was previously the Weapons Engineering Section Chief, Armament Sustainment Division. He led 13 civilian, military, and contract engineers to sustain and modernize all USAF medium caliber (20mm and 30mm) guns, bomb racks, small arms, and Special Operations weapon (25mm, 40mm, and 105mm) supporting B-1, B-2, B-52, A-10, F-15, F-16, F-22, CV-22, and AC-130. He is the recipient of several awards including the USAF Modeling & Simulation Award (2015), Robins AFB Director’s Choice Science, Engineering, & Technical Management (2015), AF LifeCycle Management Center (AFLCMC) Technical Leadership (2014), and Robins AFB Engineering & Technical Management Mid-Career Civilian (2008) awards.